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Flares as a Means of Destroying Volatile Organic and Toxic Compounds

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by

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16. ABSTRACT The paper discusses the use of flares to destroy volatile organic and toxic compounds. Flares are used to destroy industrial gases from which the heating value cannot be economically recovered. In 1980, total gases flared had a heating value of over 369 million kJ. Because most of the gases flared are considered to be volatile organic compounds (VOCs) and many are toxic, there is concern over the efficiency of this combustion process. Results of an EPA investigation of overall flare combustion efficiency and specific compound destruction efficiency, using a large pilot scale facility built in 1982, show that, for the gases tested, combustion and destruction efficiencies are above 98% if the ratio (lower heating value of gas being flared)/(minimum lower heating value required for stable combustion) is greater than 1.2. If this stability ratio falls below 1.2, the efficiencies fall rapidly, reaching zero when the flame goes out. The results also show that the stability limit is strongly influenced by the velocity and lower heating value of the gas leaving the flare tip and the design of the flare tip. A pilot flame can improve stability by extending the stable combustion regime to lower values of the lower heating value. Air and steam assist, used to reduce smoking, can affect combustion efficiency only if the assist gas flow rate is excessive.

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Toxicity	Stationary Sources	13H
Flaring	Industrial Gases	21B
Combustion		07D
Gases		07C
Organic Compounds		20M
Volatility		

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Abstract

Flares are used to destroy industrial gases from which the heating value cannot be economically recovered. In 1980, total gases flared had an aggregate heating value of over 3.5×10^{11} Btu (3.69×10^{11}kJ). Because most of the gases flared are considered to be volatile organic compounds (VOCs) and many are toxic, there is concern as to the efficiency of this combustion process. EPA has been investigating overall flare combustion efficiency and specific compound destruction efficiency using a large pilot scale facility constructed in 1982. Results of this work show that, for the gases tested, combustion and destruction efficiencies are above 98% if the ratio (lower heating value of gas being flared)/(minimum lower heating value required for stable combustion) > 1.2. If this stability ratio falls below 1.2 then the efficiencies fall rapidly, reaching zero when the flame goes out. The results also show that the stability limit is strongly influenced by the velocity and lower heating value of the gas leaving the flare tip and the design of the flare tip. Presence of a pilot flame can improve stability by extending the stable combustion regime to lower values of the lower heating value. Air and steam assist, used to reduce smoking, can affect combustion efficiency only if the assist gas flow rate is excessive.

Introduction

Flares are used to destroy industrial gases from which the heating value cannot be economically recovered. The gases flared are typically the results of purges, leaks, excess production, and emergency releases. As shown in Table A, approximately 16 million tons* of such gases were flared in 1980 from petroleum production, refineries, blast furnaces, coke ovens, and the chemical industry[1]. The estimates are uncertain because the flow of gases to flares is rarely measured. Nearly every gaseous compound handled by these plants is at one time or another sent to a flare. Most are considered as volatile organic compounds (VOCs); many are also toxic.

Combustion efficiency of large industrial flares has not been measured and is not likely to be until technology is developed which would allow remote sensing[2]. Industrial flare flames may be elevated 400 ft above ground, burn gases on heads 12 ft in diameter, and produce flames over 400 ft long.

* To convert to metric equivalant, please use the conversion factors listed at the end of this paper.

Prior to the initiation of a pilot scale flare program by the U. S. Environmental Protection Agency (EPA), direct measurements of flare combustion efficiency had been performed on pilot and small commercial scale flare flames. The results of these early tests (Table B) show that combustion efficiency could vary from 55 to 100%. The combustion efficiency values are uncertain due to several factors including an inability to close a material balance, infrequent soot concentration measurements, often-employed single point emission sampling, and difficulties caused by the intermittent nature of flare flames. A major objective of the EPA large pilot scale program was to develop techniques which would overcome these shortcomings.

The EPA flares program was initiated in 1980. A large flare test facility was constructed in 1982. This paper describes the facility and the results from the extensive test program conducted over the ensuing 5 years. The following discussion draws heavily on prior publications which describe the work in greater detail[1-8] and a soon-to-be published report on the last phase of the work completed to date.

Discussion of Results

Description of Flare Test Facility

The Flare Test Facility (FTF) was designed and constructed for EPA by Energy and Environmental Research Corporation at their Irvine, CA, location[1]. The FTF, shown schematically in Figure 1, has the following major capabilities.

- o Accommodates flare heads up to 12 in. in diameter.
- o Allows collection of samples for analysis of combustion and destruction efficiencies.
- o Allows measurement of all flowrates and other critical parameters.
- o Capable of blending any combination of available gases.
- o Capable of testing steam and air assisted flares.

The FTF was built at the end of a box canyon to provide some wind protection. Wind screens attached to the sides of the 20 by 30 by 60 ft high scaffolding enclosing the flare head provided additional wind protection. The flare head under test was installed at the top of a 12 ft tall riser. A 13 ft 8 in. square hood was suspended above the flame to collect all combustion products. Samples were withdrawn from a duct above the hood for detailed analysis of the mixed flame plume. In addition, a five point rake probe was located below the hood to measure detailed chemical specie profiles in the flame. The concentrations of O_2, CO_2, CO, HC (hydrocarbons), SO_2, and soot were determined as input to the combustion efficiency calculation. The specific compound being flared was analyzed to evaluate destruction efficiency. Gases were maintained in heated lines to avoid condensation until water was removed by Permapur^R driers. Samples were simultaneously withdrawn from each rake point into Tedlar bags for 20 min to average flame fluctuations. Gases were analyzed using continuous monitors and corrected for background concentrations and dilution. Soot was collected on a filter at the end of the probe; its mass was determined by burning it from the filter.

Matrix of Parameters Investigated

The parameters investigated to date are listed in Table C. This list includes the most recent tests described in a draft report to be published soon. The majority of the early tests, burning a propane/N_2 mixture, were devoted to developing an in-depth understanding of the basic stability and combustion efficiency characteristics of a number of flare tip designs[2,5,7]. Once these characteristics were defined for propane/N_2 mixtures, the program moved on to investigate the effects on them of other flare gases and the destruction efficiency on specific gaseous mixtures[6,8]. In all testing, the flare gas velocity was limited by the height of the sampling rake above the flare tip. To obtain a true measure of the combustion and destruction efficiency, it was necessary that the combustion reaction be completed before the flame reached the rake. Typically, flame length (height) increases with flare tip diameter for a constant velocity and combustion gas concentration. Therefore, for the largest tips tested (12 in.), gas velocity was limited to 15 fps compared to over 900 fps for the 1.5 in. diameter tip.

Table C shows the gas mixtures tested. As noted previously, a propane/N_2 mixture was chosen for the initial work to establish stability limits and combustion efficiency characteristics for various tip designs as a function of velocity and lower heating value (LHV) content. This mixture was also used to evaluate steam and air assist and the effect of pilots. Steam or air assist is commonly employed by industry to reduce the smoke plume; it is not intended to have a major effect on efficiency or stability. The desired effect is achieved by the increased mixing promoted by the assist gas. Carbon particles are formed in regions where there is insufficient air (O_2) to achieve complete combustion. In these pockets of reduced O_2 the fuel molecules pyrolyze forming nearly pure, sub-micron carbon particles which leave the combustion zone without sufficient residence time at a high enough temperature to be reduced to CO_2.

Discussion of Results

Flame Stability Versus Combustion Efficiency - Perhaps the most fundamental question to be answered by this work were what is the combustion efficiency of typical flare flames? and how is it affected by flame stability? (See next paragraph.) Intertwined was the question, what factors determine flame stability? This work found that combustion efficiency of unassisted flames was greater than 98% when the flame was stable for all gases tested. For a given flare head design, flame stability was found to be a function of the gas being burned, gas velocity at the flare tip, and the LHV of the gas. Using as a typical example, the results of tests with a 3 in. straight pipe flare burning a propane/N_2 mixture, Figure 2 shows that, for a given velocity, a minimum LHV is required for stable combustion. As velocity is increased, the minimum LHV required also increases. Figure 3 shows that combustion efficiency remains above 98% as long as the ratio of the LHV to the minimum LHV required for stable combustion (stability limit) is > 1.2. When this ratio falls below 1.2, the combustion efficiency falls off very rapidly, reaching zero when the flame goes out.

This characteristic was found to hold true for all the gases tested; however, the stability limit was found to be a function of the gas being burned, flare tip design, and presence or absence of a pilot flame.

The flame stability limit is approached when the flame propagation speed of the gas approaches the relief gas velocity. The flame will go out if the gas velocity exceeds the flame propagation speed of the gas mixture. The determination of flame propagation speed is very complex, involving reaction kinetics and mixing patterns. It is not necessarily a requirement that the gas velocity at the flare tip be less than the flame speed for stable combustion. It does mean, however, that there must exist a region in the plume where the gas velocity is less than the flame propagation speed, the concentration of combustible gas is greater than the lower flammability limit, and the temperature is above the ignition point. Furthermore, the flame must be able to propagate from this stable region throughout the gas plume to achieve high combustion and destruction efficiencies. The stability limit is reached when any one of the above criteria are not met. Most commonly, it is reached with low LHV high velocity mixtures because by the time the velocity has dropped below the flame speed by diffusion into the atmosphere, the concentration and/or the temperature are too low to sustain combustion.

Effect of Gas Composition - Gas composition was found to exert a major influence on the stability limit. Figure 4 illustrates the results obtained while burning various gases with straight pipe flare tips. Comparing the stability limit for propane/N_2 to that for H_2S/N_2 mixtures at a velocity of 10 fps shows that the latter mixture is stable at a LHV of 210 Btu/ft^3, whereas the former mixture required a LHV in the range of 400 to 500 Btu/ft^3 for stable combustion. The LHV for propane is 2350 Btu/scf compared to 588 Btu/scf for H_2S. At the stability limit for H_2S/N_2 mixtures the concentration of H_2S is actually higher than the concentration of propane at its corresponding stability limit. This and/or better combustion kinetics for H_2S may explain its ability to maintain a stable flame at a lower heat input.

Figure 4 shows that ethylene oxide (EtO)/N_2 and 1,3-butadiene (but)/N_2 mixtures also were able to maintain stable flames at leaner gas concentrations compared to propane/N_2. Methyl chloride/propane/N_2 and propane/CO_2 mixtures required higher heat input on the same basis. Over the range of concentrations evaluated, natural gas/CO_2 mixtures required less heat input compared to propane/N_2 mixtures. The toluene/propane/N_2 mixtures showed substantially the same stability characteristic as propane/N_2; however, the maximum toluene concentration did not exceed 5%. Even at this low concentration, however, toluene did show a substantial increase in the smoking tendency of the flame.

Combustion efficiency is a measure of the amount of total combustible material in a gas mixture that actually burned. Figures 5 and 6 show data for a number of mixtures. It can be seen that the combustion efficiency for the various mixtures falls in the same range as for propane/N_2 mixtures. There are too few data points to draw any additional significance from these data.

Destruction efficiency is a measure of the reduction in mass of a given species as it passes through the flame front. It is [1 - (the mass of that species entering)/(the mass of that species leaving)] x 100. A high destruction efficiency does not necessarily mean that that species was completely burned (products of incomplete combustion may not be considered). As shown in Figures 7 and 8, the destruction envelope for the mixtures tested is similar to, but perhaps more restricted than, the combustion efficiency envelope.

Combustion and destruction efficiencies generally exceeded 98% for stable flames (stability ratio > 1.2). Stability ratio is defined as the LHV at the test condition divided by the minimum LHV required for stable combustion at the test gas velocity.

Effect of Flare Head Design - As noted in Table C, a number of flare head designs were tested during this project. These included 3, 6, and 12 in. straight pipe heads and a number of commercial designs provided by flare manufacturers. Most of the commercial heads and the straight pipe heads were designed to be operated with and without air or steam assist. Therefore, comparing the results with and without assist directly may include some uncertainty due to this difference. However, since the use of an assist gas is intended primarily as a means of controlling smoke and not stability or efficiency, the direct comparison is felt to be valid.

It is important to note, however, that too high an assist gas flow can be detrimental to combustion efficiency. The assist gas acts as a diluent and as a quench gas. If the assist gas flow rate is too high it will dilute and quench the flame before combustion is complete, lowering combustion efficiency. In tests on a commercial, steam assisted flare with an exit cross-sectional area of 27 $in.^2$, the results suggested that a steam to flare gas mass flow ratio above 3.5 resulted in a significant drop in combustion efficiency[4]. This ratio is above normal design and operating practice.

Figure 9 compares the results for the straight pipe and three commercial head designs. It is obvious that the commercial heads exhibit a much wider stability range, which is achieved through the use of various stabilizing features such as flame retention rings. Flame retention rings and similar devices improve stability by creating a local low velocity region which can continue to burn stably and serve to pilot the rest of the gas stream even though the main stream velocity exceeds the minimum required for that LHV.

Tests on straight pipe flares as small as 0.042 in. in diameter up to 12 in. showed that 1.5 in. was the minimum diameter which produced results comparable to commercial flares. For most of the tests investigating gas mixture and pilot effects, a 3 in. straight pipe head was used to ensure realistic simulation of commercial applications. Within facility limitations, this size head allowed tests over a wide range of gas velocity without consuming excessive quantities of test gases.

Effect of Pilots on Stability - Every flare needs an external ignition source to initiate combustion. Most industrial flares employ continuous pilots fueled with a convenient fuel such as natural gas. One would suspect that a pilot should improve the stability limit since the pilot flame will remain stable at all flare conditions thus serving as a low velocity region and having a similar effect to the low velocity region created by flame retention devices. This hypothesis was borne out by tests on 3 and 6 in. open pipe flares burning propane/N_2 mixtures. For these flares, operated with an exit velocity of 40 fps, the minimum LHV required to maintain a stable flame was about 540 Btu/scf. A 2 scfm natural gas pilot lowered the minimum LHV for the 3 in. flare to 150 Btu/scf including pilot gas contribution. For the 6 in. flare, the same LHV reduction was possible with a 1 scfm natural gas pilot (see Figure 10). Higher natural gas flowrates and multiple pilots did not yield any substantial gain over the single 1 scfm pilot. It may be that typical, large commercial flares (48 in. in diameter) might show more benefit from multiple pilots.

Results of Modeling Studies

The preceding discussion has utilized the relationship between the LHV and flare exit gas velocity to illustrate the test results. This is a useful relationship; however, each gas composition, head design, etc. produces a different characteristic curve or set of curves. This approach does not lend itself to using this relationship for predicting, or modeling, results for parameters such as other gas mixtures not tested. One would like to find a method of normalizing the data such that all the data fall along a single curve or family of curves. To date, the search for just such a normalizing function or functions has not produced correlations substantially better than the LHV versus velocity relationship used in the above discussions.

To illustrate two alternative approaches explored, consider first the concept of a relationship between the LHV of a gas at the lower flammability limit in still air versus flare exit velocity. If the LHV of different gases at their lower flammability limit are of similar magnitude, then all of the data gathered to date should group together in families of curves associated with the design of the nozzle. Figure 11, which tests this approach for the 3 in. straight pipe data, shows that, indeed, the results for but/N_2, propane/N_2, propane/CO_2, natural gas/CO_2, and EtO/N_2 do close together quite nicely. However, the methyl chloride/ propane/N_2 and H_2S/N_2 data fall outside the group. This is probably due to the fact that the LHV at the lower flammability limits in still air for the latter two gases are different from the values for the gases in the other group which all have similar limits.

A second alternative approach is to divide the flare gas LHV at the stability limit by its LHV at its lower flammability limit in still air. This ratio is then plotted against flare exit velocity. This approach, shown in Figure 12, produces no better correlation than the previous approaches. It does show that, with increasing flare exit velocity, the heating value of most gases tested must increase to maintain a stable

flame. An exception is the methyl chloride/propane/N_2 mixtures where it was found that flame stability was correlated with the H/Cl molar ratio of the gas mixture rather than LHV. It also shows that even the mixtures with the lowest LHV must have a (LHV)/(LHV at lower flammability limit) ratio of at least 3.

Many other approaches to normalizing the data generated have been pursued without any better success. Assuming that some correlation does exist, one must assume that more data are needed, not only from flare tests of other gas mixtures, but also from investigations into fundamental flame properties such as flame speed and reaction kinetics before a suitable normalizing approach can be developed.

Impact of These Data on EPA Regulations

The data taken with the FTF have resulted in revisions to EPA flare regulations. 40CFR60, Section 60.18, added by 51 FR 2701, January 21, 1986, placed several requirements on flare operators. Restrictions were placed on the range of exit velocities and LHVs allowed. In summary this Section states that the LHV must be 300 Btu/scf or greater for steam or air assisted flares and 200 Btu/scf or greater for nonassisted flares. Steam assisted and nonassisted flares must have exit velocities less than 60 fps unless the LHV is greater than 1,000 Btu/scf in which case the allowable velocity is calculated by a formula with an upper limit of 400 fps. For air assisted flares the maximum allowable exit velocity is calculated by another formula. This Section also requires that flares be operated with a flame present at all times and that they be designed and operated with no visible emissions except for periods not to exceed a total of 5 min during any 2 consecutive hours. The complete text of Section 60.18 is in Figure 13.

ENDNOTES

Metric Equivalents

To convert nonmetric units used in this paper for the reader's convenience, to their metric equivalents, please use the following conversions.

Nonmetric	Times	Yields Metric
Btu	1.055	kJ
ft	0.305	m
ft^3	28.3	litres
HP	9.809	kW
in.	2.54	cm
$in.^2$	6.45	cm^2
lb	0.454	kg
ton	907	kg
psig	6.895	kPa
scfm	0.02832	m^3/s

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Table A. Estimate of the amount of gas flared in the United States in 1980[1]

Industry	Production of product 10^6 tons/yr	Percent flared	Amount flared 10^6 tons/yr	Heating value 10^{12} Btu/yr
Refineries	1048	0.2	2.1	103
Petroleum Production	584	0.5	2.9	116
Blast Furnaces[a]	146	6.6	9.6	69
Coke Ovens[a]	55	0.4	0.2	11
Chemical[a] Industry	60	2.0	1.2	59
Total			16.0	358

[a]Combustible gases only

Table B. Combustion efficiency of flare flames measured in previous studies[5]

Study	Date	Flare size in.	Design	Velocity fps	Gas flared	Measured efficiency percent
Palmer	1972	0.5	Experimental Nozzle	50 - 250	Ethylene	>97.8
Lee & Whipple	1981	2.0	Holes in 2 in. Cap	1.8	Propane	96 - 100
Siegel	1980	27.[a]	Commercial Flaregas Coanda FS-6	0.7 - 16	Refinery Gas[b]	97 - >99
Howes, et al.	1981	6.[c]	Commercial Air Assist. Zink LH	40 - 60	Propane	92 - 100
Howes, et al.	1981	3 at 4[d]	Commercial H.P.Zink LRGO	Near Sonic (estimate)	Natural Gas	>99
McDaniel	1983	8	Commercial Zink STF-S-8	0.03 - 62	Propylene/ Nitrogen[e]	67 - 100
McDaniel	1983	6[c]	Commercial Air Assist. Zink STF-LH-457-5	1.4 - 218	Propylene/ Nitrogen[f]	55 - 100

(a) Opening of a cone on an FS-6 Coanda flare head
(b) 50% hydrogen plus light hydrocarbons
(c) Supplied through spiders; high Btu gas through area of 5.30 $in.^2$ and low Btu gas through 11.24 $in.^2$
(d) Three spiders, each with an open area of 1.3 $in.^2$
(e) Heating value was varied from 209 to 2183 Btu/scf
(f) Heating value was varied from 83 to 2183 Btu/scf

Table C. Flare test parameters

Flare head design	Diameter in.	Gas mixture[a] A	B	C	D	E	F	G	H	I	J	K	Pilot fuel[b] scfm	Assist Pressure psig	Air scfm	Steam lb/lb fuel	Flare exit velocity fps Low	High	Gas heating value Btu/scf Low	High	Comments	Ref.
Straight	3.0	x											2.1				1.9	209	76.1	495		6
pipe	3.0											x					0.15	9.6	336	877		6
"	3.0					x											0.67	139	370	757		6,8
"	3.0							x									0.30	9.2	145	510		6
"	3.0						x										0.99	32.5	170	331		8
"	3.0	x											2.1-8.1				17.2	148	99	377		8
"	3.0			x													0.264	103	385	2350		
"	3.0			x									0.99				1.03	86.6	239	815		
"	3.0				x												0.94	10.1	385	482		
"	3.0				x								1.0-2.2				10.2	11.7	239	345		
"	3.0									x							0.89	57.6	542	774	3.0-6.82[c]	
"	3.0									x			0.9-2.4				0.24	39.2	169	890	3.2-11.4[c]	
"	3.0										x						0.95	100	391	497		
"	3.0								x								0.32	9.11	176			6
"	3.0	x															0.5	80	376	1325		5
"	3.0	x														0.14-1.0		428	792	2350		5
"	6.0	x															1.0	12	291	1323		5
"	6.0	x														0.32-0.56		2.9		1318		5
"	6.0	x											1.0-5.0				5.6	44.7	40.8	264	1 pilot	8
"	6.0	x											2.0				10.2	47.6	65.1	165	2 pilots	8
"	6.0	x											2.0				12.9	49.6	79	160	3 pilots	8
"	12.0	x															0.2	4.1	385	1323		5
"	12.0	x														0.46		4.0		1323		5
Commercial A	12.0	x															0.2	4.5	392	1318		5
Commercial B	12.0	x															0.3	6.2	303	1316		5
Commercial B	12.0	x														0.44		5.9		1311		5
Commercial C	12.0	x															0.65	14.6	371	1328		5
Commercial C	12.0	x														0.46		13		1314		5
Commercial D	12.0	x														0.07-3.7	0.17	9.9	261	425	Coanda head	6
Commercial E	1.5	x												0-10			14	907	371	1130		6
Commercial F	3.8	x												0-4			4.4	158	139	453		6
Commercial G	1.5	x													1100		0.73	591	189	2350		6

(a) Code — Gas mixture (in N_2 except as noted)

Code	Gas mixture (in N_2 except as noted)
A	Propane
B	Natural gas
C	Propane in CO_2
D	Natural gas in CO_2
E	H_2S/propane
F	H_2S
G	1,3-butadiene
H	Ethylene oxide
I	Methyl chloride/propane
J	Toluene/propane
K	Ammonia/propane

(b) Natural gas used as pilot fuel
(c) H/Cl molar ratio

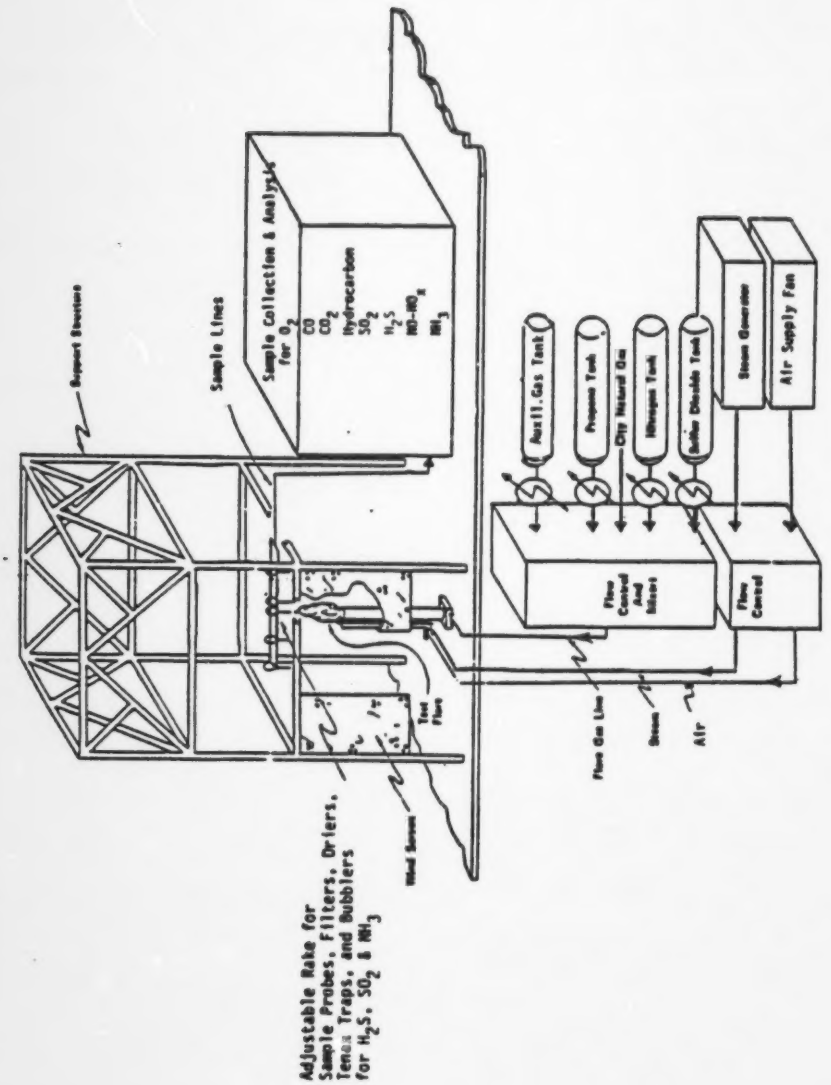

Figure 1. EPA flare test facility (FTF) at EER.[6]

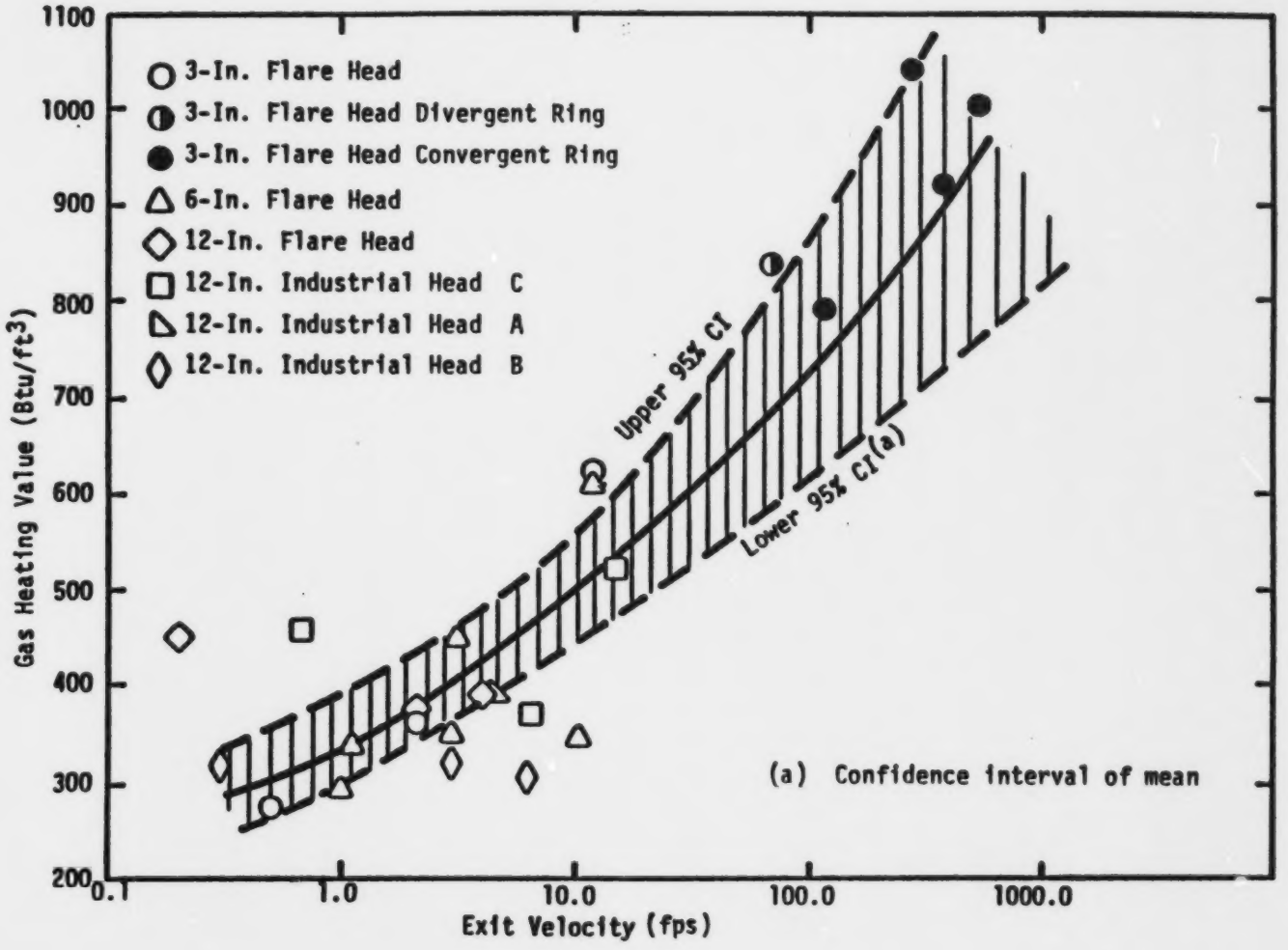

Figure 2. Region of flame stability for propane/nitrogen mixtures with no pilot flame.[5]

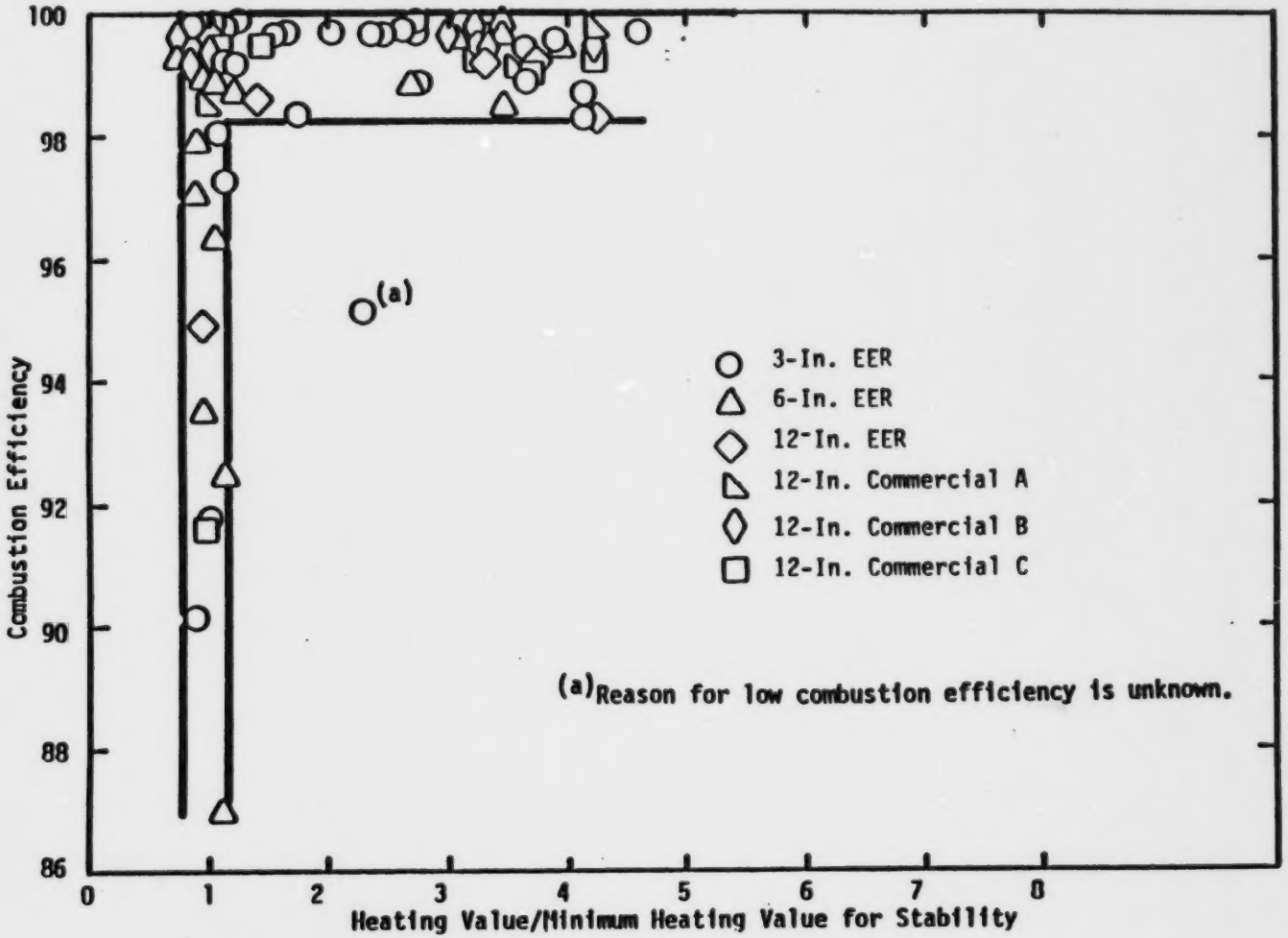

Figure 3. Combustion efficiency of flares burning propane/nitrogen mixtures with no pilot flame near the lower limits of flame stability.(5)

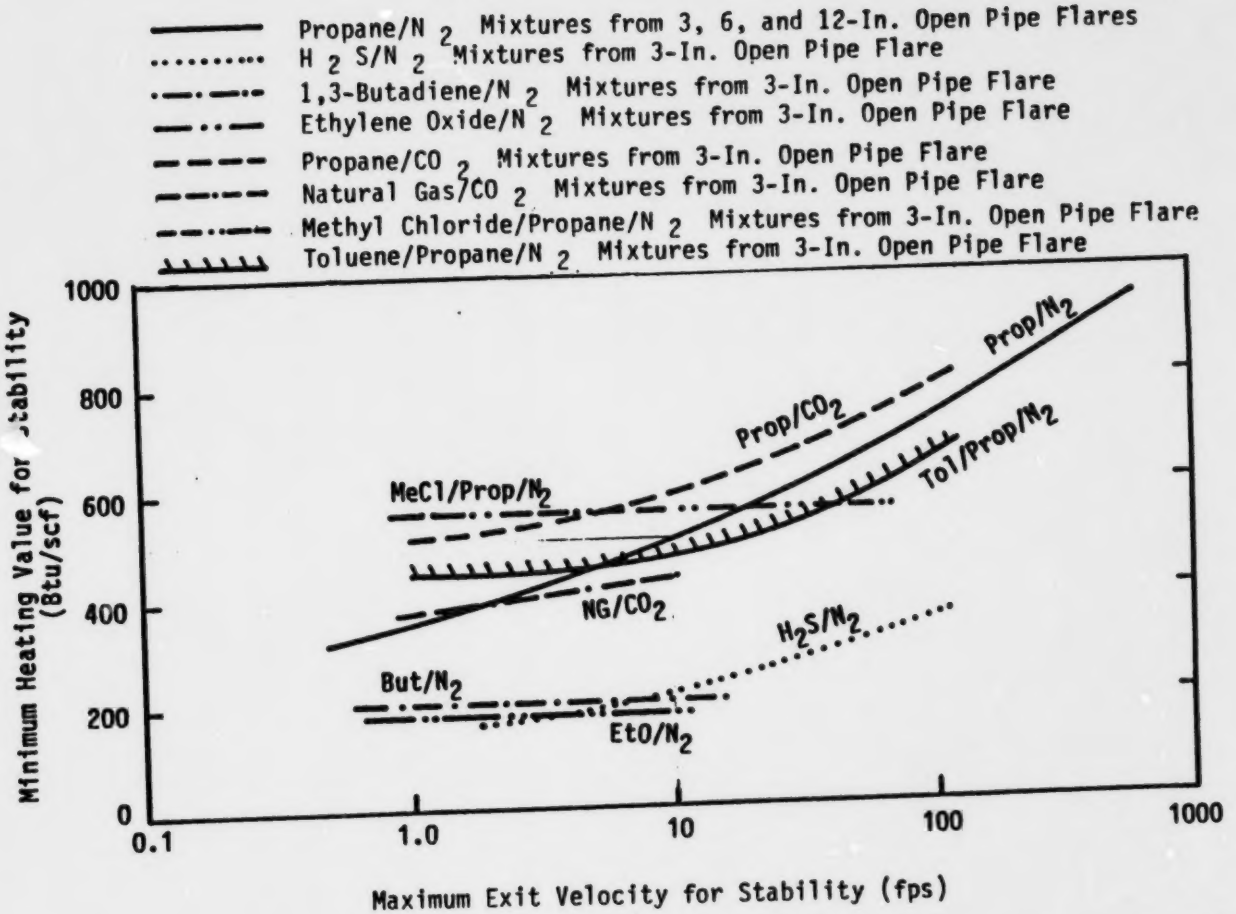

Figure 4. Flame stability limits for different gas mixtures flared without pilot assist from a 3-in. open pipe nozzle.

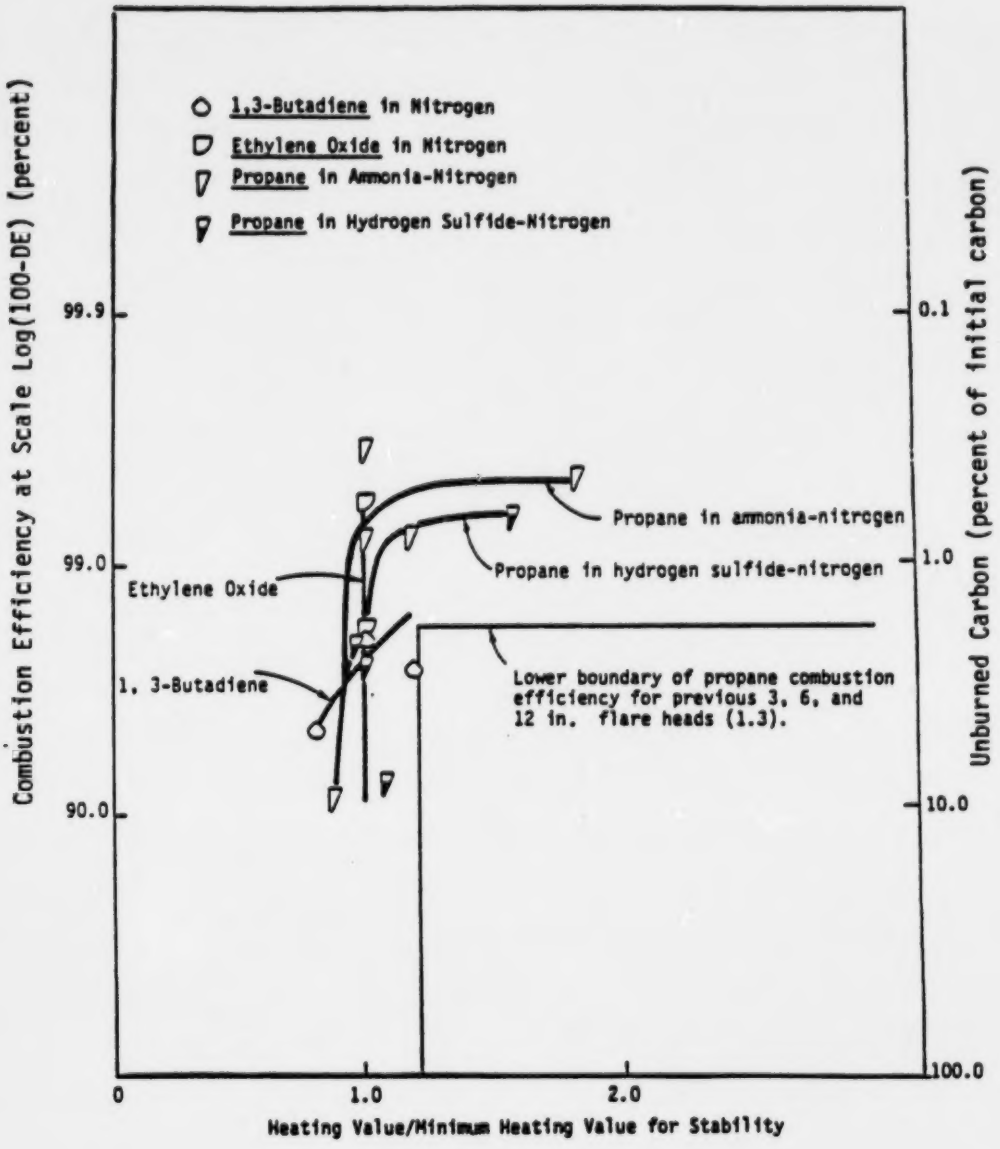

Figure 5. Hydrocarbon combustion efficiency of gas mixtures.[6]

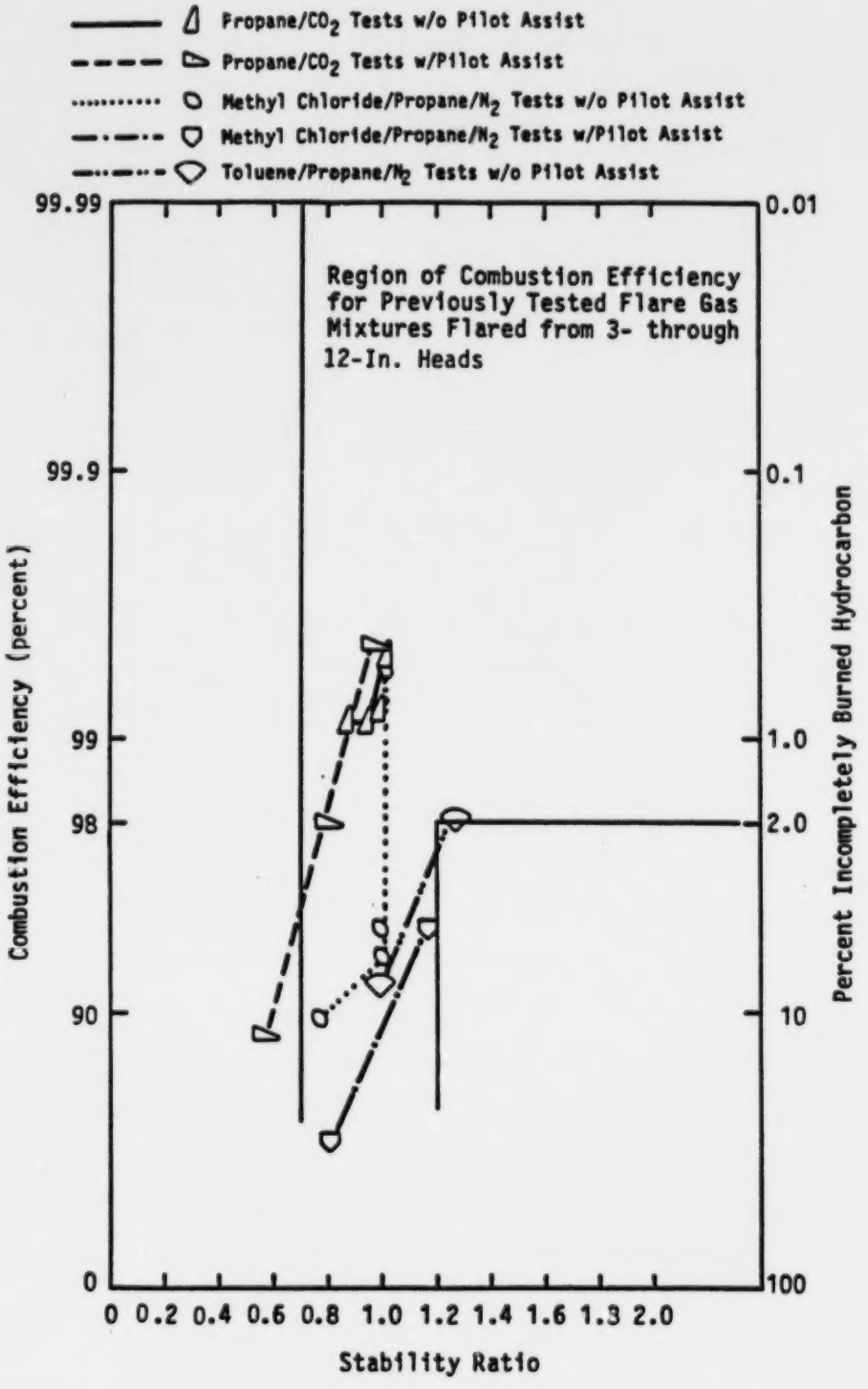

Figure 6. Combustion efficiency compared to the flame stability ratio.

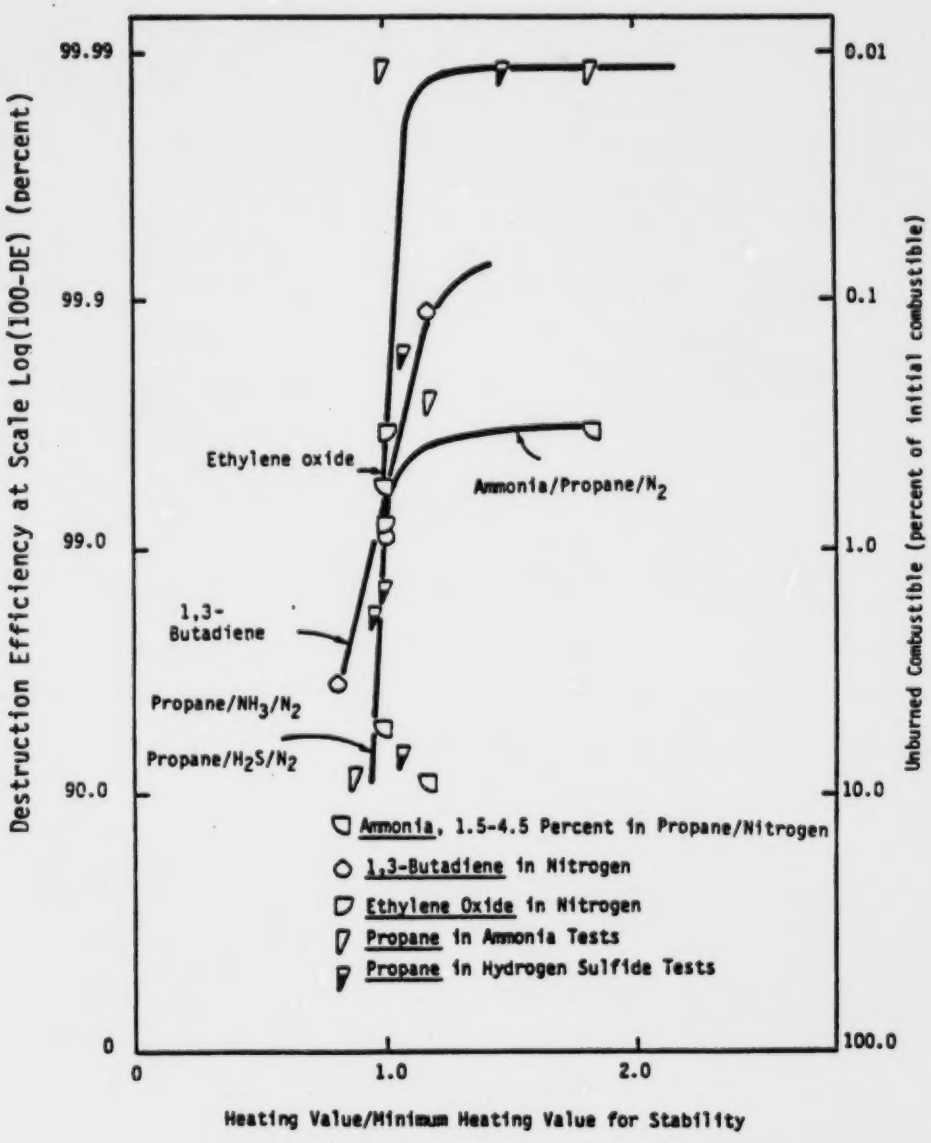

Figure 7. Destruction efficiency of different gases.(6)

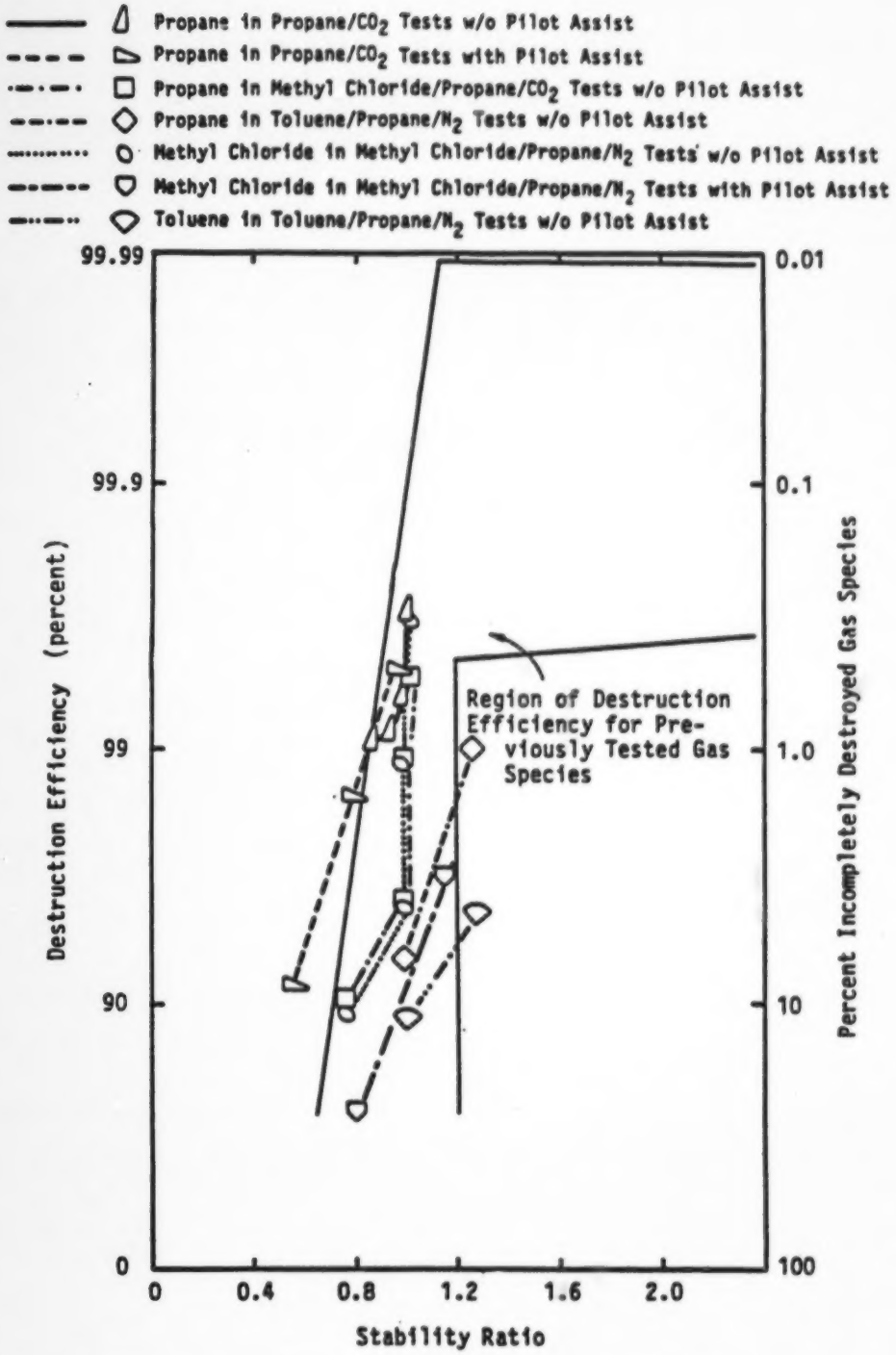

Figure 8. Destruction efficiency of individual gas species compared to the flame stability ratio.

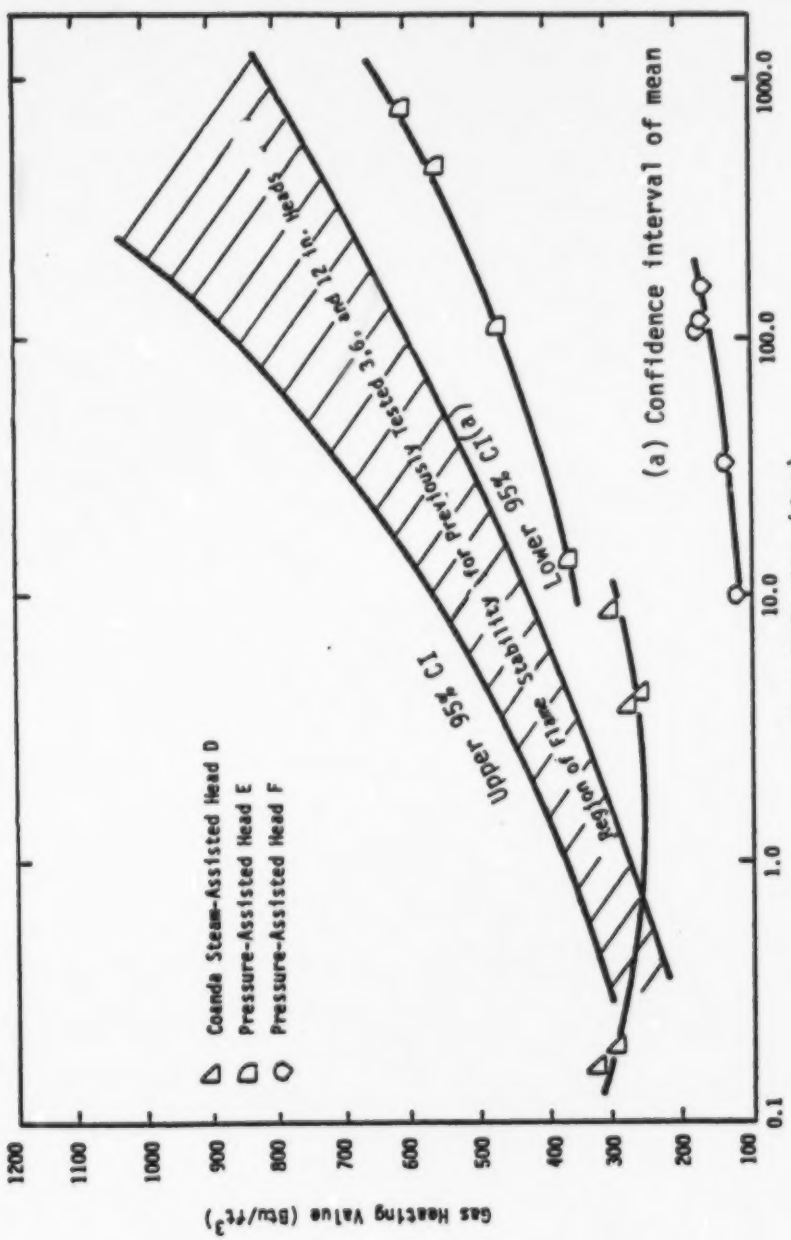

Figure 9. Region of flame stability for steam and pressure-assisted heads D,E, and F.(6)

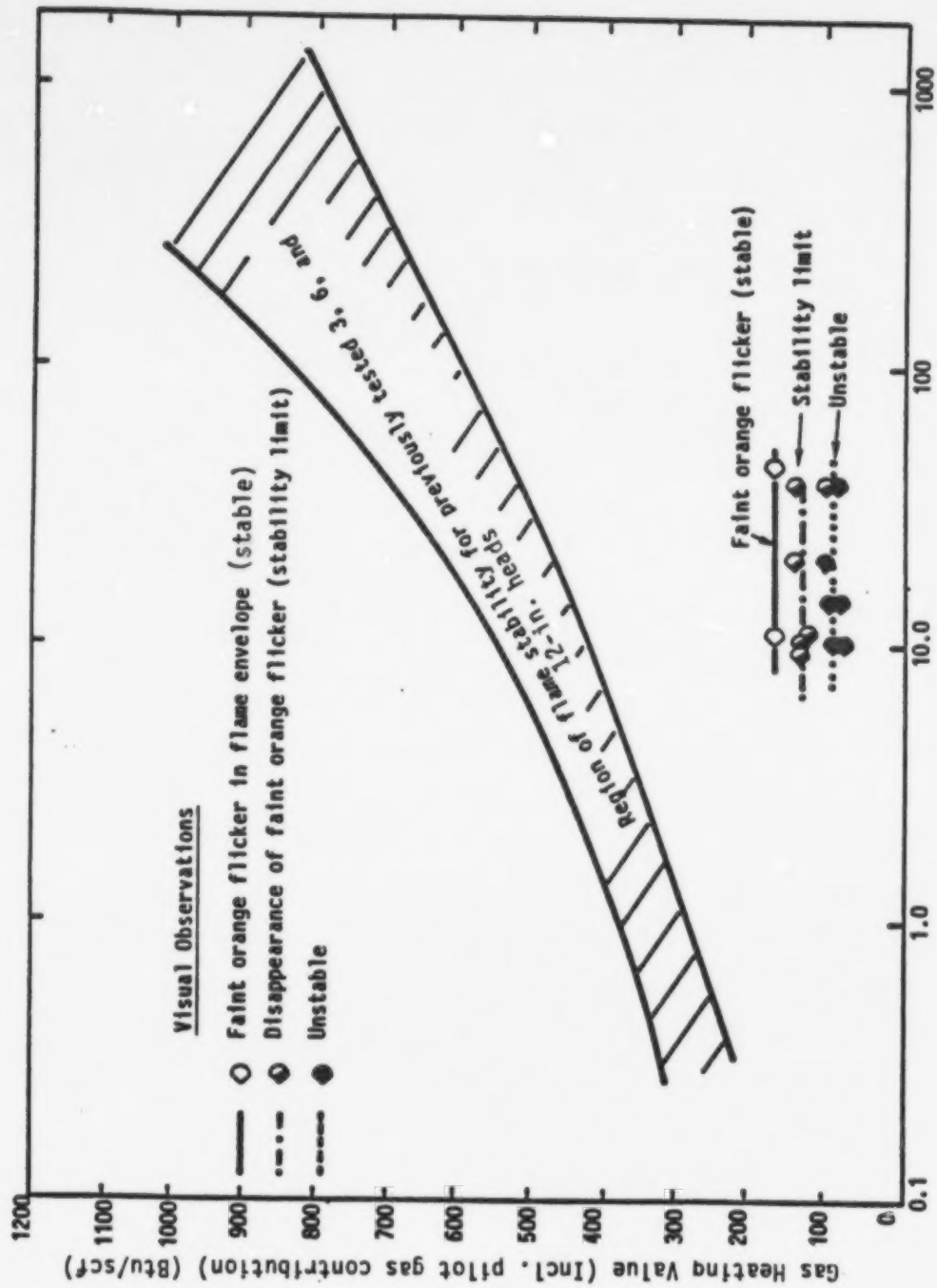

Figure 10. Flame stability curves for 6-in. open pipe flare with a single pilot at a pilot gas flowrate of 1.0 - 1.1 scfm natural gas.[8]

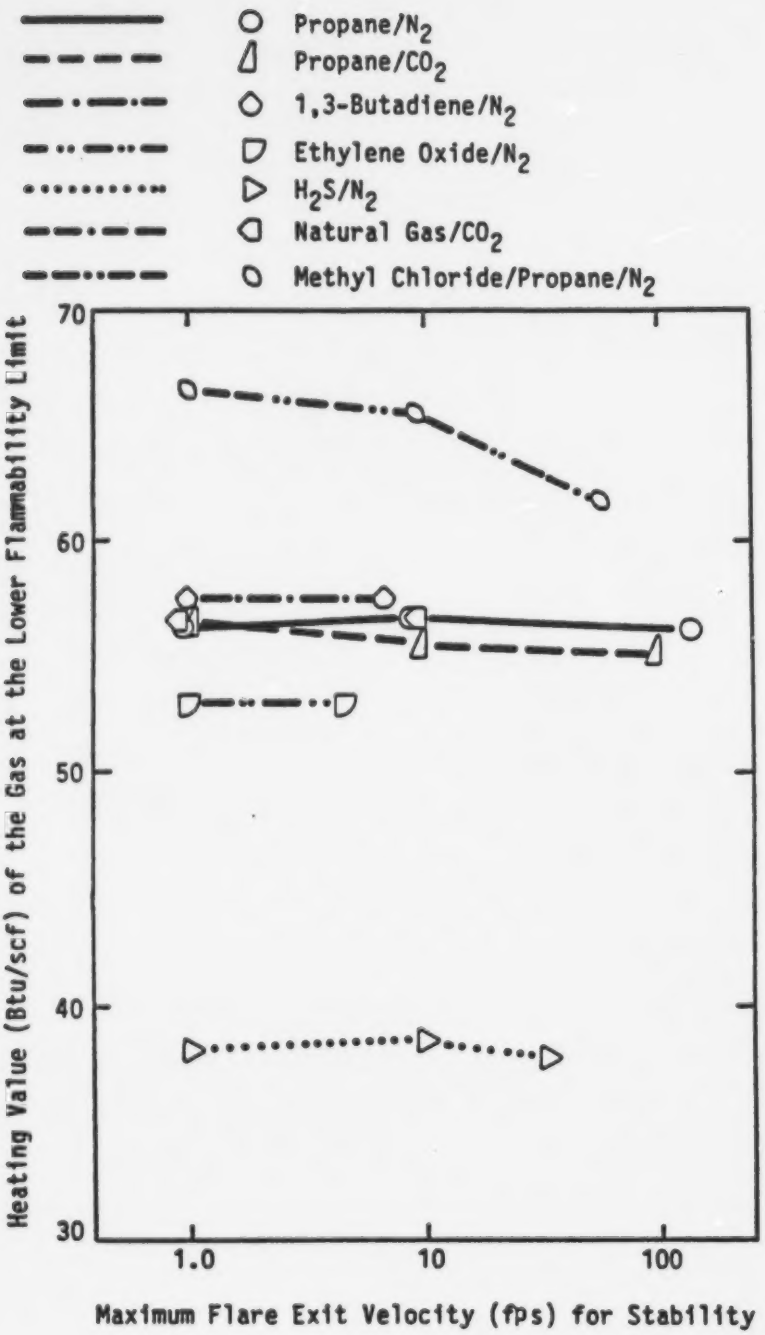

Figure 11. Heating value of lower flammability limit mixture of flare gas and air.

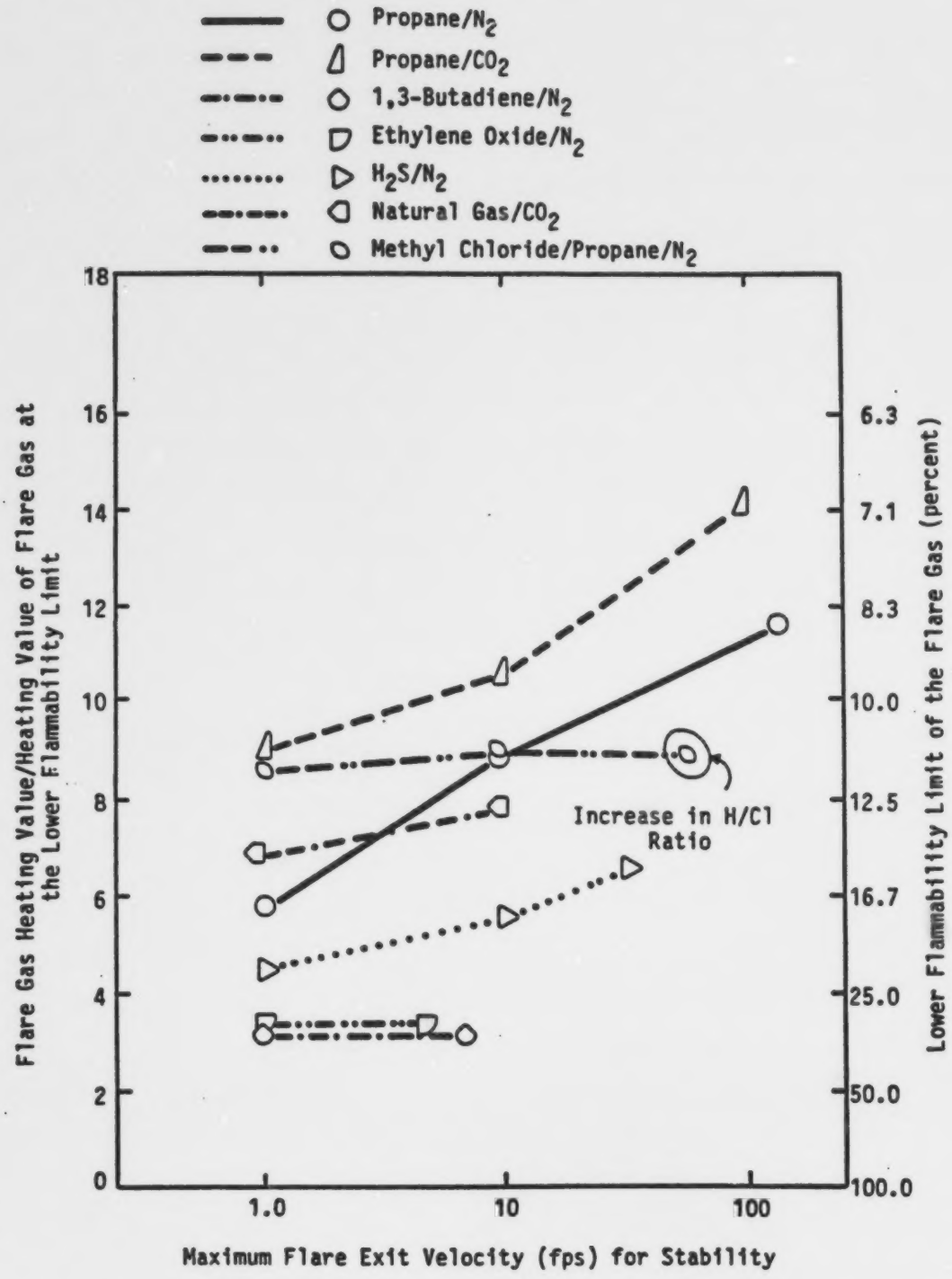

Figure 12. The ratio of the flare gas heating value divided by the heating value of the flare gas at the lower flammability limit.

§60.18 General control device requirements.

[60.18 added by 51 FR 2701, January 21, 1986]

(a) *Introduction.* This section contains requirements for control devices used to comply with applicable subparts of Part 60 and Part 61. The requirements are placed here for administrative convenience and only apply to facilities covered by subparts referring to this section.

(b) *Flares.* Paragraphs (c) through (f) apply to flares.

(c)(1) Flares shall be designed for and operated with no visible emissions as determined by the methods specified in paragraph (f), except for periods not to exceed a total of 5 minutes during any 2 consecutive hours.

(2) Flares shall be operated with a flame present at all times, as determined by the methods specified in paragraph (f).

(3) Flares shall be used only with the net heating value of the gas being combusted being 11.2 MJ/scm (300 Btu/scf) or greater if the flare is steam-assisted or air-assisted; or with the net heating value of the gas being combusted being 7.45 MJ/scm (200 Btu/scf) or greater if the flare is nonassisted. The net heating value of the gas being combusted shall be determined by the methods specified in paragraph (f).

(4)(i) Steam-assisted and nonassisted flares shall be designed for and operated with an exit velocity, as determined by the methods specified in paragraph (f)(4), less than 18.3 m/sec (60 ft/sec), except as provided in paragraph (b)(4)(ii) and (iii).

(ii) Steam-assisted and nonassisted flares designed for and operated with an exit velocity, as determined by the methods specified in paragraph (f)(4), equal to or greater than 18.3 m/sec (60 ft/sec) but less than 122 m/sec (400 ft/sec) are allowed if the net heating value of the gas being combusted is greater than 37.3 MJ/scm (1,000 Btu/scf).

(iii) Steam-assisted and nonassisted flares designed for and operated with an exit velocity, as determined by the methods specified in paragraph (f)(4), less than the velocity, V_{max1} as determined by the method specified in paragraph (f)(5), and less than 122 m/sec (400 ft/sec) are allowed.

(5) Air-assisted flares shall be designed and operated with an exist velocity less than the velocity. V_{max} as determined by the method specified in paragraph (f)(6).

(6) Flares used to comply with this section shall be steam-assisted, air-assisted, or nonassisted.

(d) Owners or operators of flares used to comply with the provisions of this subpart shall monitor these control devices to ensure that they are operated and maintained in conformance with their designs. Applicable subparts will provide provisions stating how owners or operators of flares shall monitor these control devices.

(e) Flares used to comply with provisions of this subpart shall be operated at all times when emissions may be vented to them.

(f)(1) Reference Method 22 shall be used to determine the compliance of flares with the visible emission provisions of this subpart. The observation period is 2 hours and shall be used according to Method 22.

(2) The presence of a flare pilot flame shall be monitored using a thermocouple or any other equivalent device to detect the presence of a flame.

(3) The net heating value of the gas being combusted in a flare shall be calculated using the following equation:

$$H_T = K \sum_{i=1}^{n} C_i H_i$$

where:

H_T = Net heating value of the sample, MJ/scm; where the net enthalpy per mole of offgas is based on combustion at 25 °C and 760 mm Hg, but the standard temperature for determining the volume corresponding to one mole is 20 °C;

$$K = \text{Constant}, 1.740 \times 10^{-7} \left(\frac{1}{ppm}\right) \left(\frac{g\ mole}{scm}\right) \left(\frac{MJ}{kcal}\right)$$

where the standard temperature for $\left(\frac{g\ mole}{scm}\right)$ is 20°C;

V_{max} = Maximum permitted velocity, m/sec

8.706 = Constant

0.7084 = Constant

H_T = The net heating value as determined in paragraph (f)(3).

C_i = Concentration of sample component i in ppm on a wet basis, as measured for organics by Reference Method 18 and measured for hydrogen and carbon monoxide by ASTM D1946-77 (Incorporated by reference as specified in § 60.17); and

H_i = Net heat of combustion of sample component i, kcal/g mole at 25 °C and 760 mm Hg. The heats of combustion may be determined using ASTM D2382-76 (incorporated by reference as specified in § 60.17) if published values are not available or cannot be calculated.

(4) The actual exist velocity of a flare shall be determined by dividing the volumetric flowrate (in units of standard temperature and pressure), as determined by Reference Methods 2, 2A, 2C, or 2D as appropriate; by the unobstructed (free) cross sectional area of the flare tip.

(5) The maximum permitted velocity, V_{max} for flares complying with paragraph (c)(4)(iii) shall be determined by the following equation.

$$\text{Log}_{10}(V_{max}) = (H_T + 28.8)/31.7$$

V_{max} = Maximum permitted velocity, M/sec

28.8 = Constant

31.7 = Constant

H_T = The net heating value as determined in paragraph (f)(3).

(6) The maximum permitted velocity, V_{max}, for air-assisted flares shall be determined by the following equation.

$$V_{max} = 8.706 + 0.7084\ (H_T)$$

Figure 13. Flare regulations 40CFR60, Section 60.18